Space Technology in Support of Cooperative US-Ukraine Efforts to Mitigate the Damage at the Chornobyl Unit 4 Nuclear Power Plant

David Lavery
Headquarters, Code S
National Aeronautics and Space Administration
Washington, DC 20546

Neville I. Marzwell
Jet Propulsion Laboratory - California Institute of Technology
National Aeronautics and Space Administration
Pasadena CA 91109

Maynard A. Holliday
Lawrence Livermore National Laboratory
U.S. Department of Energy
Washington D.C. 20024

James Osborn
National Robotics Engineering Consortium
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract

For transitional economies like Ukraine that have legacies from the Soviet era of severe environmental damage due to accidents and years of neglect, space technology-based remote systems can play an important role in evaluating and remediating hazardous sites. Developing countries and transition economies can avail themselves of this technology with technical and financial assistance to mitigate the risk to their populations in monitoring, evaluating and cleaning up hazardous sites.

Project Pioneer is one such application of space technology to this acute problem. Pioneer is a cooperative project between Ukraine and the United States of America to develop and deploy a remote robotic structural diagnostic system at the Chornobyl Nuclear Power Plant (ChNPP). In both space and ground missions, there is technology requirements synergy for robots to survive in harsh environments and for intelligent remote operation with minimal human support. NASA technologies developed for Mars Exploration that will be implemented in Pioneer include remote teleoperation; photo-realistic 3-D visualization of stereo-based range mapping capable of hazardous environment operations and an in-situ coring system for sample acquisition. DOE technologies developed for hazardous waste characterization and clean-up will also be implemented on Pioneer such as a high precision robotic manipulator and integrated science instruments with radiation hardened sensors. A model for cooperation between scientific organizations has emerged with the Inter-Branch Scientific and Technical Center of the ChNPP contributing prior Chornobyl robotics experience to the team during its acceptance testing and deployment and the US providing technical support during initial system deployment.

Other countries can use this technology through collaborations with bi-lateral and multinational nuclear safety programs. The U.S. Department of Energy's International Nuclear Safety Program which is a co-sponsor of the work at Chornobyl is one mechanism. Also the Nuclear Safety Account at the European Bank for Reconstruction is active in lending to countries of the

Former Soviet Union to improve safety at their nuclear power plants. Specifically, Russia has expressed interest in collaborating with the U.S. on co-developing robotics for hazardous clean-up operations at their nuclear sites.

Follow-on work will include the integration of additional imaging and environmental sensors as well as other robotic devices like dirigibles and micro-rovers for site characterization.

Introduction

There is a worldwide need for field robotics technology to support environmental restoration of nuclear facilities. A key resource is a set of compatible component technologies – mobility systems, communication and control technologies, sensing and modeling methods, tooling and work packages – that can be quickly configured into purpose-built, low-risk, high impact work systems. The availability of these systems will enable major environmental restoration projects around the world: dismantlement and cleanup of government weapons complex sites, remediation of ordnance stores, nuclear power plant decommissioning, and environmental accident response.

Decommissioning of nuclear or hazardous facilities, whether accident damaged or not, requires extensive remote capabilities including:

- obstruction removal to enable facility access for remediation activities
- characterization and monitoring of contamination levels, structural integrity, and other features of the environment which must be known to plan and execute the job
- sampling and source removal
- demolition and retrieval of contaminated materials
- waste packaging and transport

To signal the maturation of these technologies, an international team is addressing one of the most visible and dramatic environmental restoration problems in the world – the stabilization of the Chornobyl Unit-4 accident site. The threat of a criticality event within the Chornobyl Unit-4 "Ukritiye" or Shelter is a constant priority. Recent elevated neutron measurements within the shelter have raised concern to a heightened level and prompted a renewed sense of urgency. Criticality issues are compounded by the frequent application of thousands of gallons of water to control dust emissions from the shelter. As such, the situation at Unit-4 requires swift, definitive action.

The initial work regarding Chornobyl Unit 4 stabilization involves structural diagnostics within the Shelter. Operational planning for future stabilization and remediation activities within the Shelter requires various types of information regarding the physical integrity and physical characteristics of the shelter.

The Pioneer program, led by US DOE, is producing a radiation hardened telerobotic mobile vehicle for nuclear facility characterization with particular focus on structural diagnostics (sensing and sampling). NASA is providing technologies that give added value to the mobility platform in the context of Chornobyl Unit 4 stabilization. These include:

> <u>Remote presence and visualization:</u> Due to extreme radiation levels, visual inspection of the structure must be performed remotely. Further, a key component of the structural assessment itself entails geometric measurements and comparisons against baseline as-built conditions. Both of these requirements are being satisfied by a system to process stereo imagery, and merge range maps and appearance data acquired as the robot moves through the facility to produce a 3-D model that is both visually and geometrically correct. The 3D mapper is a tool useful for archiving other data and for planning future activities.
>
> The 3D Mapper will be used to create a complete three-dimensional (3D) model of the interior of the reactor. Applying stereo vision and visualization technologies developed for Mars Pathfinder, dozens of pictures will be taken from many different locations, and will be combined into a single overall model. Once built, that model will allow scientists

to "fly-through" the virtual world, which not only looks like the original environment but also has the properly reconstructed shape. The model will also be used to take 3D measurements of the interior without actually being inside the facility. In this way the volume of rubble, location of equipment, and viable pathways can all be determined without human exposure to radiation.

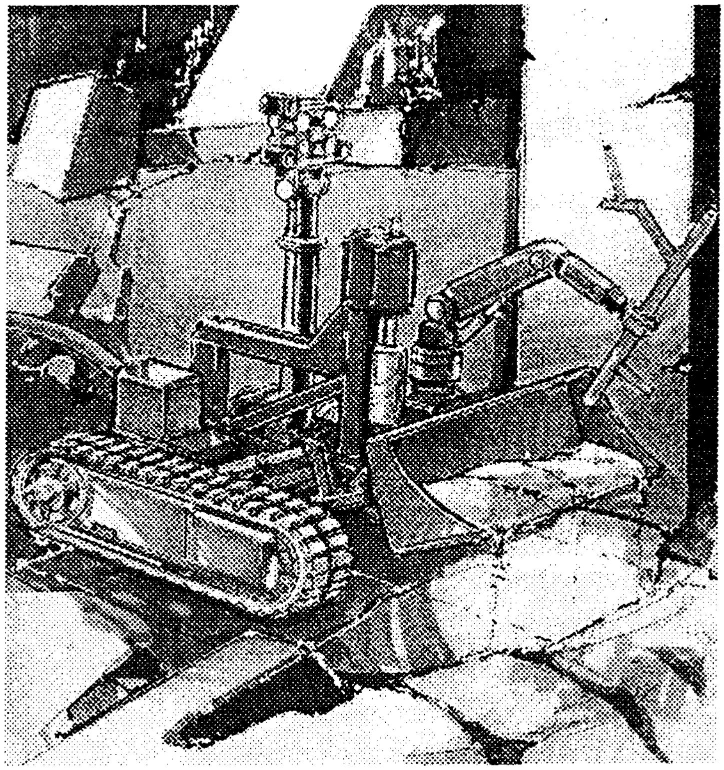
Coring and sampling: Since the primary remote work task is to evaluate the integrity of structural elements of the Unit-4 Shelter, physical sample acquisition is an activity that should be performed in early missions. Initially, this will involve deploying a core boring system to return concrete samples from key locations.

The Pioneer Coreborer is designed to take samples from various points in the interior of the Chernobyl power plant. These samples will be taken away from the hazardous radiation environment and brought into safer areas for study. Planners will be able to gauge the deterioration of the shelter by measuring properties of these concrete samples. An important tool for this study, the Pioneer coreboring mechanism uses software originally developed for the exploration of comets and asteroids, software that is able to intelligently speed up or slow down the drill while it operates. This is the first such intelligent drill to be deployed on a mobile robot

Program Overview

Goals

A unique and historic collaboration between US government agencies, American industry and the operators and technical staff of the Chornobyl "Shelter" has been organized to create a foundation of robotic technologies that enable Chornobyl stabilization and demonstrate an initial component set to begin and forward the stabilization agenda.



The challenges posed by radiological conditions and accident debris at the damaged Chornobyl Unit-4 reactor require remote technology. In response to this need, robots will be used at Chornobyl to perform extensive characterization of the facility and ultimately the lava like fuel containing masses (LFCMs) which have flowed into lower regions of the reactor building.

This program is producing a radiation hardened mobile robot and an initial set of characterization tools, including a coring system and a 3D visualization system.

Team Composition

For the foundation program, RedZone Robotics, Inc., a Pittsburgh-based company that develops robots for use in hazardous environments is creating a mobile robot appropriate to this task in partnership with US Department of Energy (DOE). Through a Joint Services Research Agreement, NASA and the Carnegie Mellon University National Robotics Engineering Consortium are maturing and providing payloads based on technologies originating at NASA centers.

Overall technical leadership for the project is being provided by the DOE as administered by the representatives of the Lawrence Livermore National Laboratories (LLNL). Below is a summary of program participants involved in this endeavor and their roles in the project.

DOE - LLNL	Program Technical Leadership

DOE - PNNL	Program Administration
RedZone	Robotic Systems Fabrication
ISTC/ChNPP "Shelter"	Application Expertise
NREC	Technology Maturation & Productization
NASA - JPL	NASA Technology Source
NASA - AMES	NASA Technology Source
Westinghouse	Environmental Sensor Package

Technology Sources

Key technologies which contribute to this initiative come from the following organizations:

Table 1: Base Technology Sources

Source	Technology	Ownership
RedZone Robotics, Inc.	Houdini mobile vehicle platform	proprietary
NASA - JPL	Smart drilling controls/hardware Stereo vision software	public domain public domain
NASA - AMES	3D visualization	public domain
Carnegie Mellon	Remote concrete sampling 3D data processing software	proprietary public domain

System Design

Requirements

The initial work regarding the Chornobyl Unit 4 stabilization campaign involves structural diagnostics within the Shelter. Operational planning for future stabilization and remediation activities within the shelter also requires various forms of intelligence regarding the physical integrity and physical characteristics of the Shelter. Together, these motivate the following mission requirements for Pioneer:

- gaining access to the shelter, particularly the basement and fuel suppression pool areas
- visual and environmental surveying of the structure
- determining radiation exposure levels
- environment mapping (physical obstructions, radiation)
- obtaining concrete samples for structural analysis

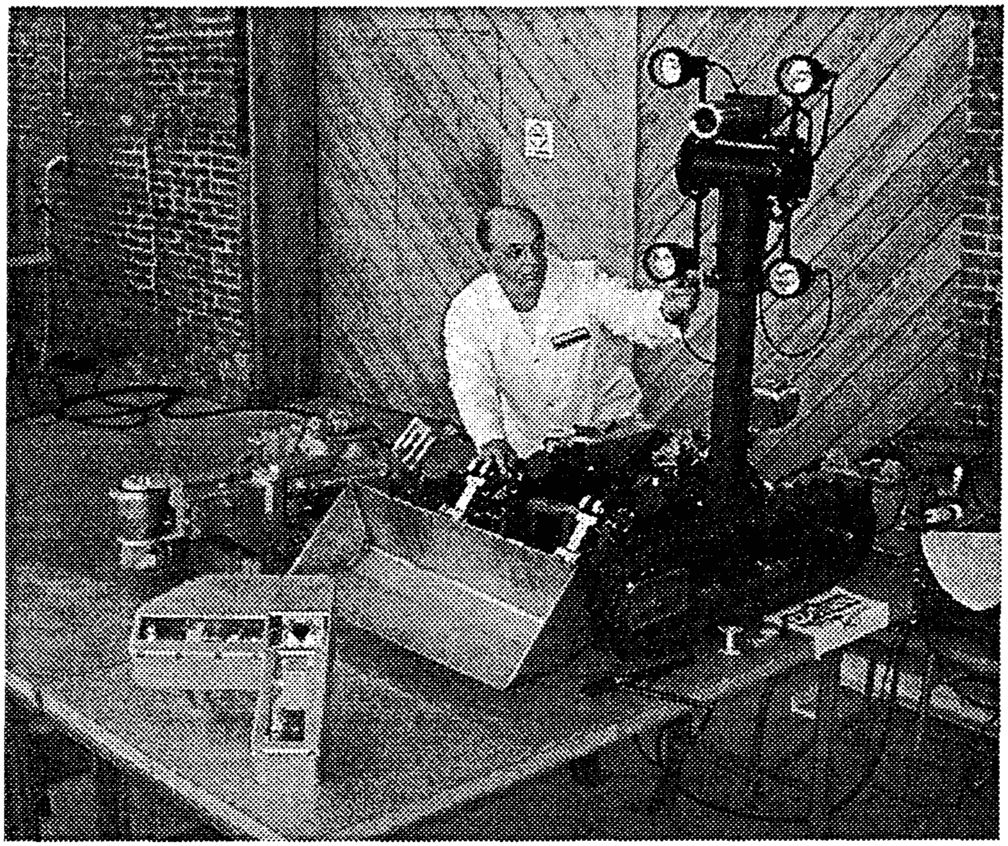
The environmental conditions within the Shelter vary between fairly benign and overtly hazardous. Areas where remote systems are of use are typically more hostile. The environmental requirements for Pioneer are characterized by:

- gamma radiation fields up to 3,500R/hr
- lifetime gamma ray dose of 1×10^6R Total Accumulated Dose
- neutron radiation fields ranging from <1 up to 1400 neutrons/cm^2/sec
- ambient air-borne dust particles containing fission product (gamma ray) radioactivity and actinide (alpha particle, beta particle, and low-energy gamma ray) radioactivity
- operating temperature -10 to 35° C (14 to 95° F)
- humidity up to 100%
- little or no ambient lighting

Solutions

Pioneer is a remote reconnaissance system for structural analysis of the Chornobyl Unit 4 reactor building. Its major components are a teleoperated mobile robot for deploying sensor and sampling payloads; a 3D mapper for creating photorealistic 3D models of the building interior; a concrete sampling drill for cutting and retrieving samples of structural materials; and a suite of radiation and other environmental sensors.

Figure 1: The Pioneer robot and payloads

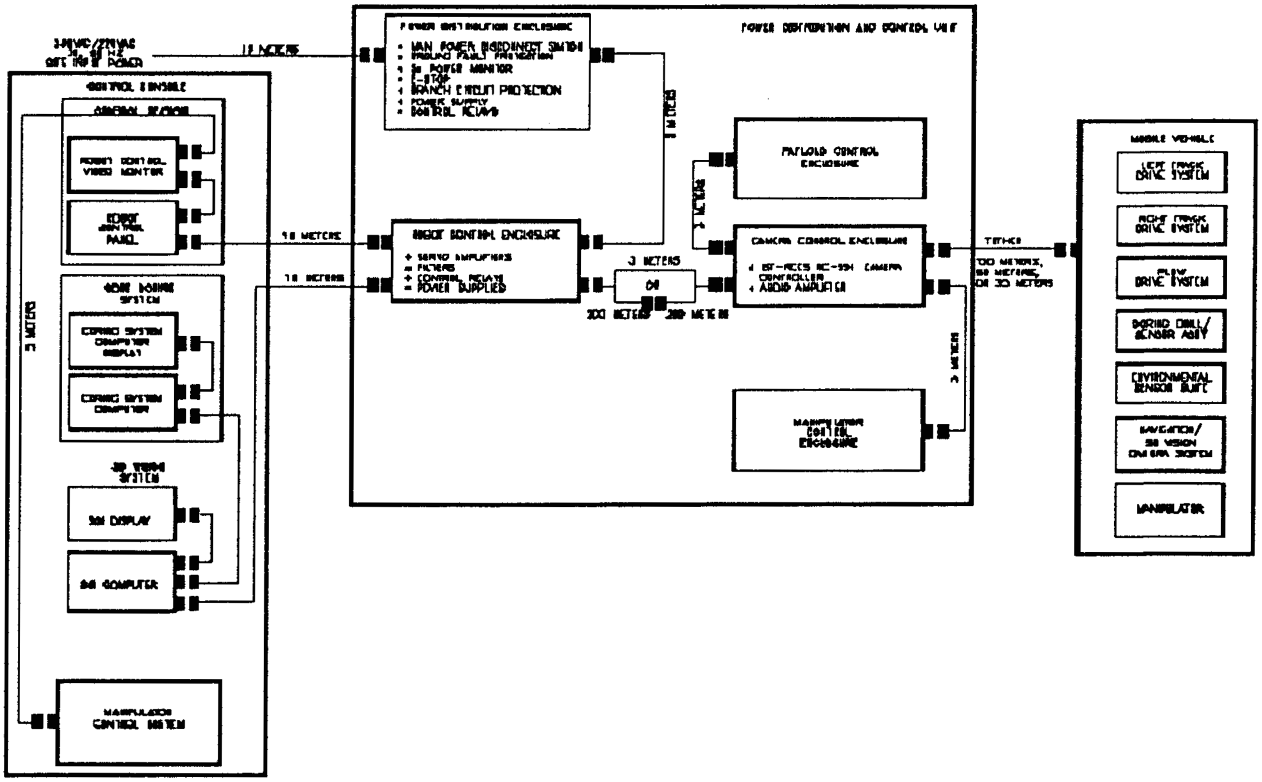


The Pioneer robot is a track-driven machine similar to a small bulldozer that is electrically powered and teleoperated via a 100 meter long umbilical. Tracked locomotion is well suited for driving over and through rubble; the robot's 1.1 x 1.4 m footprint provides ample stability and platform capacity to deploy payloads; a six degree of freedom manipulator allows positioning of sensors and tools relative to the locomotor deck. Also intrinsic to the robot is a sensor suite that includes radiation detectors, temperature and humidity sensors and a rad–hardened color video camera.

A ruggedized, portable control console provides the means to operate the robot from safe locations. The console is connected to an environmentally sealed enclosure that houses electric transformers, power supplies and conditioners, the control system, and interface electronics. The console includes joysticks, switches, and video monitors for controlling system functions and monitoring system operation. The control console incorporates ergonomic design considerations for long duration operation.

The Power Distribution and Control Unit (PDCU) can be reconfigured, depending on the application in which it will be used. However, there are several functions for the PDCU that are common despite varying design. An environmentally sealed and temperature controlled PDCU includes the electric transformers and distribution/conditioning equipment, the control system, and tether and control system interface connectors.

Figure 2: Pioneer System block diagram



Pioneer will create 3D digital reconstructions that faithfully capture both the appearance and geometry of the Unit 4 interior using stereo videography. A custom imager consisting of three black & white cameras with folded optics is deployed on Pioneer's sensor mast and positioned by a pan and tilt unit under computer control. Images that it acquires are processed to generate surface meshes that are texture-mapped with a color image. By merging adjacent meshes, large contiguous 3D maps are generated which can be analyzed by experts outside the Shelter on-site or at remote locations via the Internet. Because the scene is digital, dimensions of objects in the scene can be estimated. In the future, maps generated by Pioneer may be integrated into a more complete "Virtual Chornobyl" model for large scale visualizations and planning future work tasks.

Figure 3: Pioneer trinocular stereo camera

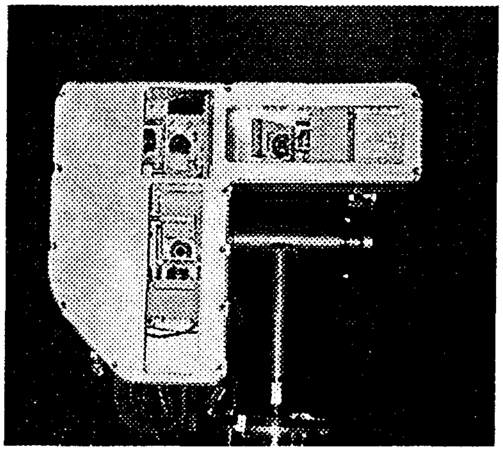
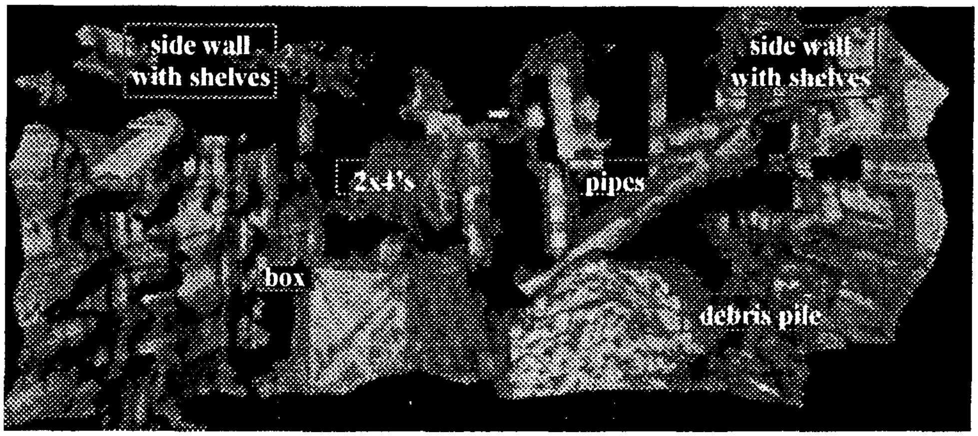


Figure 4: Early 3D mapping result



One of Pioneer's primary initial tasks is to assess the physical condition of the Unit-4 building itself. A remotely operated core sampling drill has been designed to cut and retrieve cylindrical samples of concrete floors and walls that can be subsequently analyzed for strength and brittleness. That data serves as input information to structural analysis programs. The drill consists of a linear carriage that thrusts a drill motor and bit into the target structure, and a sensor that measures reaction forces and torques during the coring process. Closed-loop computer control of both thrust and rotation helps to ensure quality of the sample and makes the process automatic. An important by-product of the approach is the ability to estimate material hardness based on the resistance and deflection measured by the drill sensors. Structural information from Pioneer's core sampler will be invaluable for assessing the building's structural integrity and correlating it to radiation and other environmental parameters.

Figure 5: Pioneer concrete sampling drill

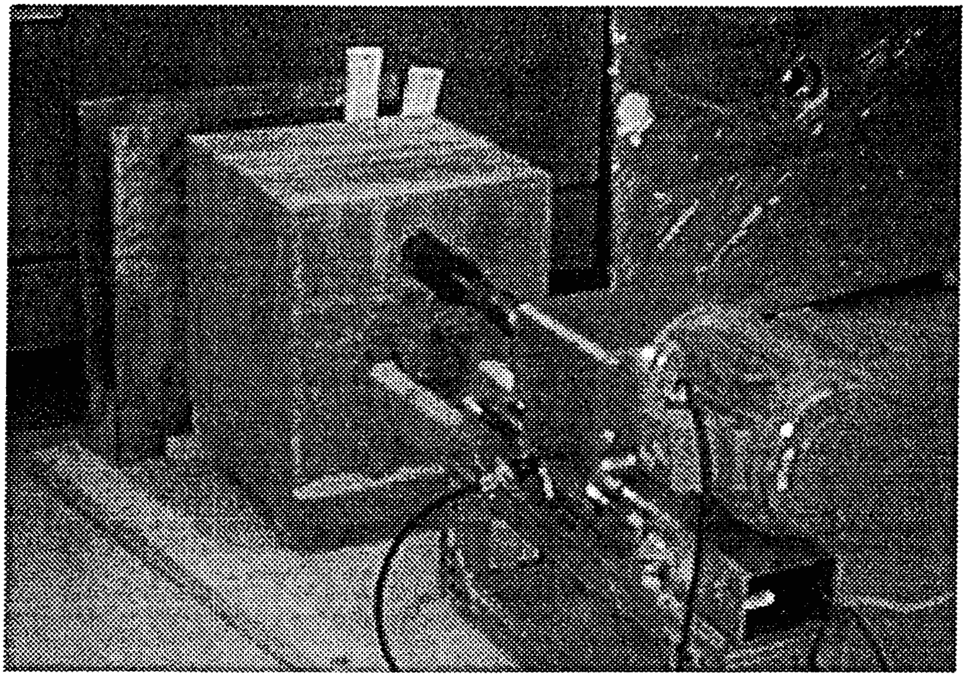
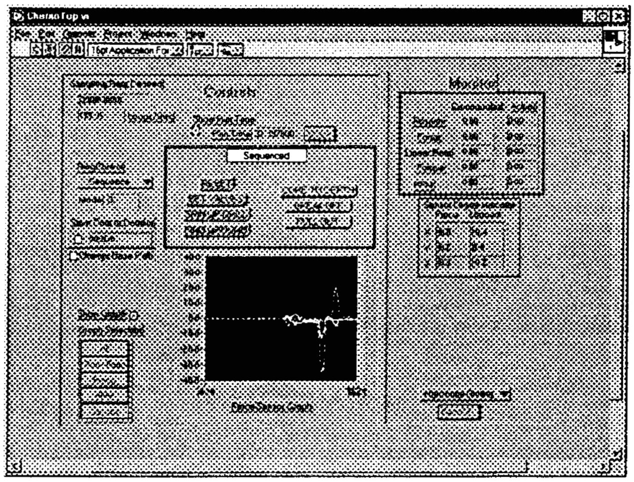


Figure 6: Drill User Interface



Simple, rugged radiation detectors will be deployed on the system to measure gamma ray fields. Because of the fact that the gamma ray fields result primarily from ^{137}Cs, gross gamma counting will suffice, and Geiger-Mueller (G-M) counters will be used. Since the lifetime in a radiation field for a G-M tube is limited by the total number of counts produced, the detector will be in the active mode only when the counter is being used to measure gamma doses, and pulsed counter interrogation methods will be used to greatly extend the counter lifetime. This detector will be supplied with sufficient shielding to permit directionality in its measurements, so that gradients in the gamma ray field intensity of the surroundings can be identified even though the detector itself is located in a high radiation field. This directionality will allow local areas with elevated gamma ray count rates to be identified during operations.

Small, gas-filled (^{3}He or BF_3) proportional counters will be used to detect neutrons. Both cadmium-covered and bare detectors will be used to detect thermal and epithermal neutrons, respectively. The thermal neutron component is expected to result from moderated neutrons from the actinides present which reach the detector directly as well as a sizable fraction which results from interactions of these neutrons with the room and its contents ("room-return" neutrons). Epicadmium or epithermal neutrons are expected to yield more useful information on the locations of the neutron sources. Therefore, the neutron detectors will be surrounded by a cadmium shield or by another suitable thermal neutron absorber such as gadolinium.

Standard thermister/thermocouple methods will be used for ambient temperature measurements. In addition, an on-board humidity sensor will allow assessment of the humidity levels where the system is located.

Robotic Technologies

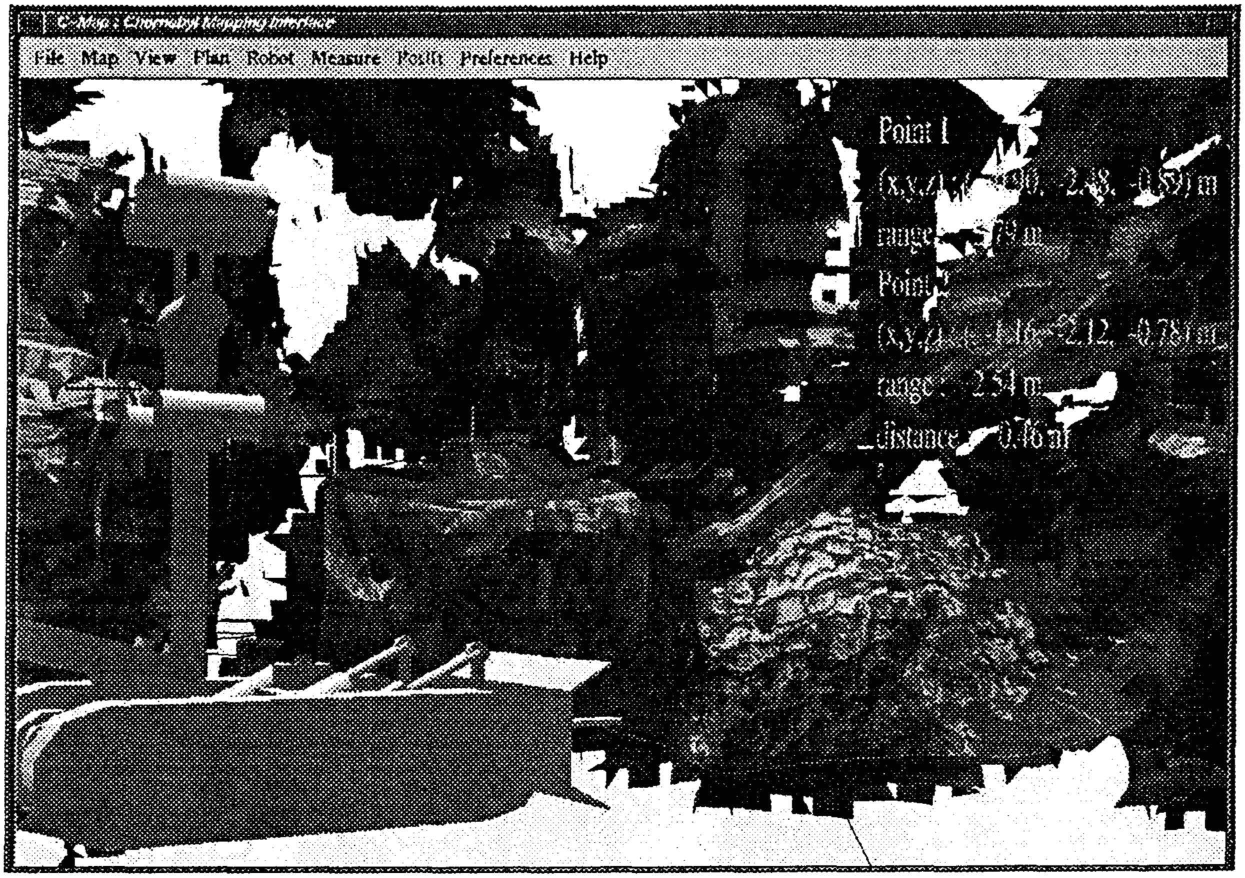
3D Mapper Sensing: JPL is providing the Stereo Vision software that automatically calculates 3D information about the environment. The JPL stereo software used on Pioneer is the result of nearly a decade of Mars Rover research. It has been demonstrated on several prototype Mars Rovers, and it was used by the human drivers during Mars Pathfinder to generate the terrain maps used to plan Sojourner's excursions.

The benefits of this technology are enormous. In a few seconds, hundreds of thousands of measurements are made, providing rich detail about the structure of the room in front of the robot. This analysis is performed automatically, as the images are collected by the robot operator. In addition, the quality of the results is automatically evaluated and immediately displayed to the operator. If the results could be improved, a message will be displayed (both English and Russian messages are available), prompting the operator to take corrective action.

3D Mapper Visualization: NASA Ames has developed an advanced user interface integrating a 3D environment for requesting, displaying and managing photo-realistic 3D models of the nuclear plant interior. The technology used for this project is a derivative of the visualization software called *MarsMap* provided for the very successful Mars Pathfinder mission. This tool allows the user to fly-through the reconstructed 3D models of the interior, to perform structural analyses, and to estimate radiation doses for mission planning as well.

The interface is designed to be useful both during the data acquisition and data analysis phases of operation. Data acquisition must be as simple and streamlined as possible, so the language of the display can be set to either English or Russian, and only simple operations requiring minimal or no typing may be performed. Data analysis uses state of the art visualization techniques to ensure the maximum communication of information to the user. NASA Ames has also developed the central Executive program that connects all the software subsystems of the Pioneer 3D Mapper together, and creates the database where all the output data are stored automatically.

Figure 7: Pioneer Mapper Analysis User Interface



Coreborer Control: JPL has developed a unique control system architecture for the Pioneer coring mechanism to extract samples from the concrete floor and walls in the Chernobyl Nuclear Power Plant. A significant portion of the expertise for this development is inherited from earlier studies in the area of exploration of interplanetary small bodies, such as comets and asteroids. JPL has developed novel technologies that allow the drilling to occur at a prescribed thrust force while archiving information on penetration rate, force variances, and subtle differences in bit interactions with the substrate. An analysis technique developed by JPL automatically determines the type of material being sampled, just from studying these measured rate changes during drilling operations.

JPL has implemented the end-to-end hardware/software interfaces, appropriate data acquisition processing and archiving, and a user-friendly graphical interface for the Pioneer Coreborer. The control system is carefully designed to meet specifications and requirements imposed by the RedZone robot's physical characteristics. In particular, special force and torque control algorithms have been implemented to ensure the safety and stability of the entire rover system. Special attention has been given to ensure robust operation of the coring mechanism in the presence of operational anomalies, uncertain environments, and material inhomogeneity or discontinuity.

Operating Scenario

The Pioneer system will undergo extensive testing both in the US and in Ukraine, prior to deployment in the Shelter. This testing will give its operators a thorough understanding of the system's capabilities and performance limitations. The system will then be disassembled into man-transportable components, carried into the Shelter, reassembled, and checked out.

Initial deployment is expected to be from Room 318/2 (a shielded control room) to a location in room 308/2 where floor core sampling and monitoring will be demonstrated. The deployment demonstrates structural sampling and environmental monitoring capabilities consistent with deployment in Room 305/2. Room 308/2 is adjacent to Room 305/2. This phase describes the operations and tasks that must be accomplished to characterize room 308/2. The successful completion of the Pioneer mission is the structural and environmental characterization of this room.

The Pioneer vehicle carries a concrete core boring tool designed to cut and remove intact samples of material located throughout the site. During a core retrieval, the vehicle operator extracts a single core of material for further testing. Once extracted, the core is deposited into a core sample container. This allows multiple samples to be taken and reduces the cycle time to take these samples. After depositing the sample, the vehicle returns to the deployment area for manual installation of a new coring bit. The core sample container can then be transported by the vehicle after all samples have been taken. Structural information is collected from both the coring process and subsequent laboratory analysis of the core sample such as compressive strength testing and petrography. The detailed operating scenario for coring is as follows:

The Pioneer system carries a Photo-Realistic 3D Mapping system, which is used to gather 3D structural information of the rooms within Chornobyl. The system is deployed on a counterbalanced pan & tilt unit. The fixed camera mast places the system of cameras approximately one meter above the floor. The system is positioned near a surface of interest. The recommended distance from objects is approximately 2 meters, and the precise resolution depends upon the distance.

Once the system is in place, the cameras are pointed toward the area of interest. The operator is provided direct video feedback, and the area mapped is approximately that in view of the feedback camera. The camera assembly is adjusted using a pan & tilt with push-button control. There is also be a display indicating the orientation of the assembly relative to the vehicle.

The vehicle also carries a package for environmental sensing. This allows radiation (gamma and neutron), temperature and humidity measurements to be taken at any location where the system is operating.

Gamma ray monitoring is carried out with a shielded Geiger-Mueller (G-M) tube. The G-M tube responds to the gross gamma ray field present, which in the vicinity of FCM, consists primarily of 137-Cs gamma rays. A removable lead collimator/shield surrounds the G-M tube. When present, the collimator provides a directional gamma ray response so that the local gamma ray intensity below the robot can be evaluated and mapped as a function of robot location. When the collimator is removed, the ambient gamma ray field experienced by the robot and its components can be evaluated.

The gamma ray detector response to core samples are calibrated using a 137-Cs source with known activity positioned within the core bore location with the core positioned in a known and reproducible location. During coring operations, the dose rate from each core can be evaluated by measuring the increase in count rate of the gamma ray counter in order to provide advance information to enable safe handling of the core when it is returned to the deployment area.

Continuous gamma monitoring data is obtained during operations in order to detect any unusual changes in radioactivity levels. Discrete gamma ray intensity measurements are taken as a function of time and robot location to provide information on gamma ray intensity contours. These measurements can be carried out on a grid pattern or, if more appropriate, on a location-of-interest basis in order to map the gamma ray fields within the area of operations of the robot.

Two neutron detectors are used to simultaneously monitor the thermal and epithermal fluxes during robot operations. The thermal neutron fluxes are not expected to vary greatly with location, but do provide a sensitive indicator of changes in the environment such as a reconfiguration of FCMs, neutron poisons, or neutron moderators (such as water). The epithermal neutron counter provides data that is more closely related to the locations of FCMs or local concentrations of neutron poisons or moderators. Neutron counts are acquired continuously during robot operations to detect any sudden changes in flux intensity. Also, discrete local count rates are obtained as a function of time and location in order to map the thermal and epithermal neutron fluxes in the area of robot operations.

Continuous temperature and humidity measurements are taken during operations of the robot, and local mapping of temperature and humidity conditions are undertaken, if appropriate.

Summary and Schedule

In an appropriate synergy, this project provides the opportunity both to perform humanitarian services and demonstrate novel space-relevant technologies in an extreme environment. By providing state of the art space technologies to industrial partners, NASA accomplishes its mandate to serve the public by transferring appropriate technologies to commercial use.

The main activities for the near term are cold testing of the robot in Ukraine following hardening of the 3D visualization and core sampling systems in Pittsburgh. Integrated system testing in Ukraine will commence by early 1999, with Unit-4 deployment following shortly.

Future efforts involve extension of remote capabilities from diagnostics to actual stabilization. Robot tasks might include remote construction, e.g., erecting steel and/or concrete to provide additional structural support; removal of debris to make way for follow-on missions by other robots; and installation and maintenance of semi-permanent sensor networks to monitor environmental conditions.

Initial deployment will be in a relatively benign portion of the Shelter to demonstrate in-field capabilities. These proving missions will be followed by entries into areas that pose significant challenges in the form of debris fields, high radiation, and complete darkness.

Acknowledgments

Several corporate, government, and academic institutions are collaborating in the development of the Pioneer robot. Primary sponsors are the Department of Energy and the National Robotics Engineering Consortium (NREC), a NASA-sponsored institute chartered to transfer NASA technology to industry. The project is supervised by Lawrence Livermore Laboratory personnel. Most of the Pioneer robot is being built by the RedZone Robotics company (Pittsburgh, PA), with the 3D Mapper and Coreborer hardware built by Carnegie Mellon University (Pittsburgh, PA). JPL provides Stereo Vision software previously demonstrated during Mars Pathfinder, Coreborer control software, and a newly-developed Camera Calibration target. NASA Ames and University of Iowa provide the 3D visualization environment demonstrated during Mars Pathfinder, and Executive control software. Thanks to Mark Maimone, Ali Ghavimi, Geb Thomas and Daryl Rasmussen for their contributions to this paper.